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TEST AND ANALYSIS OF A NORTHRUP COLLECTOR CONTROLLER

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16. ABSTRACT

The collector controller is examined as a functioning control system that drives the Northrup collector from east to west to follow the Sun then back to the east at sundown in readiness for the next sunrise. The major components are examined separately with particular emphasis placed on an analysis of the electronic drive circuit.

Results are presented from hardware testing and analysis with recommended changes to improve the system.

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INTRODUCTION

The purpose of this report is to describe the testing and analysis performed on the Northrup collector controller utilizing a new electronic circuit. Particular emphasis was placed on analysing the circuit. A brief description of the collector is given to better understand the objective of this solar energy collecting system.

The collector is a concentrating collector with a fresnel lens mounted on top of a trough-like enclosure which focuses the Sun's rays on a target near the bottom of the enclosure. The collector is gimbaled about its long axis with 1 degree of freedom east/west allowing the Sun's rays to be nearly normal to the fresnel lens surface in one plane. This focuses the solar energy on the absorber or target very close to the focal point of the fresnel lens.

BASIC CONTROLLER COMPONENTS AND THEIR FUNCTIONS

Figure 1 presents a picture of the controller as configured for testing the new electronic breadboard circuit. Figure 2 depicts a functional block diagram schematic of the controller system.

The controller consists basically of the following components:

a. Sun sensor (Mod 1)

b. Electronics (New)

c. Motor and drive train (Mod 1).

When the difference between the sensor's two solar cell outputs reaches a predetermined value based on a small angle of incidence of the Sun's rays striking the sensor, the electronic circuit energises a relay to switch 110 Vac to

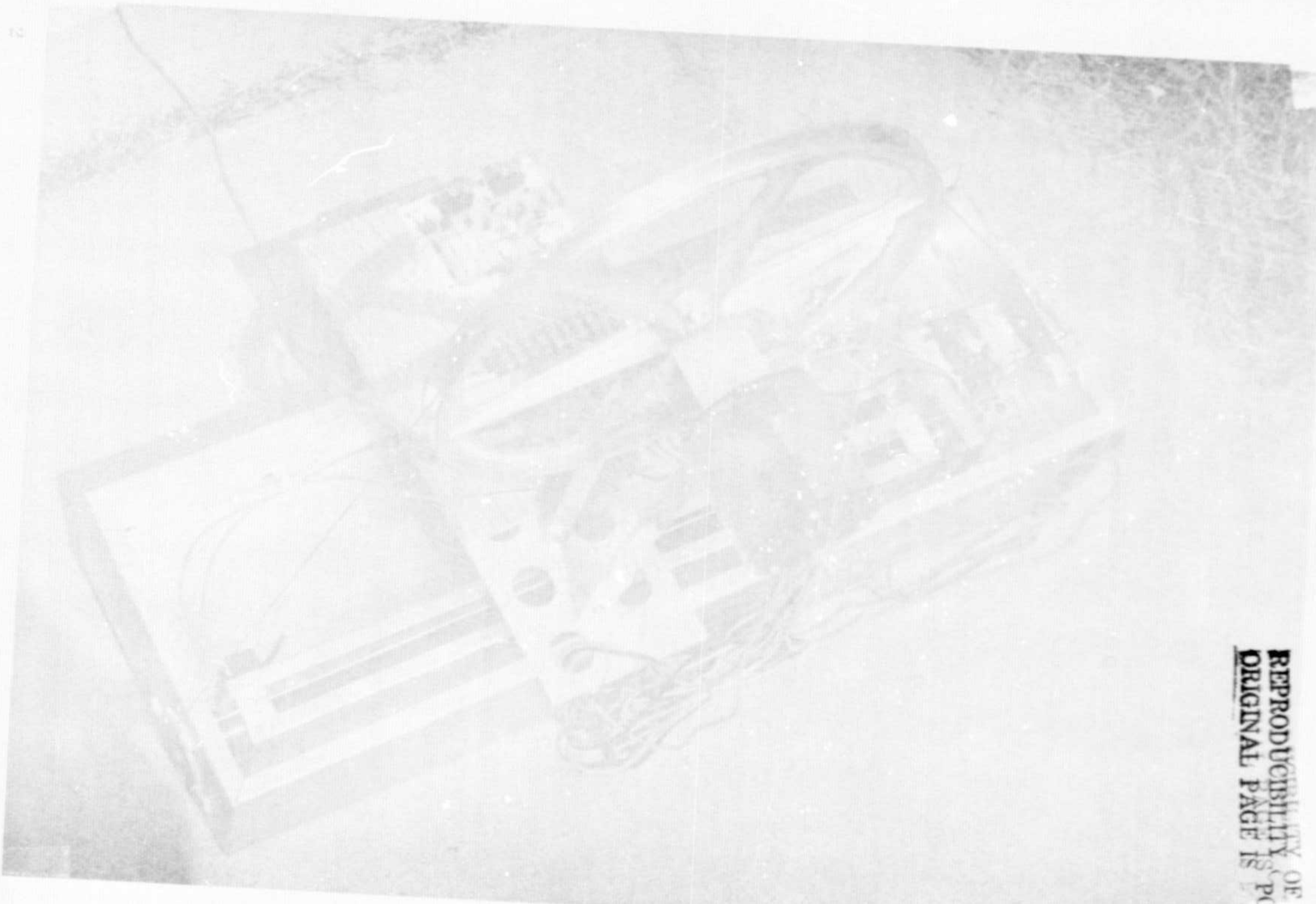

Figure 1. Controller configuration for testing.

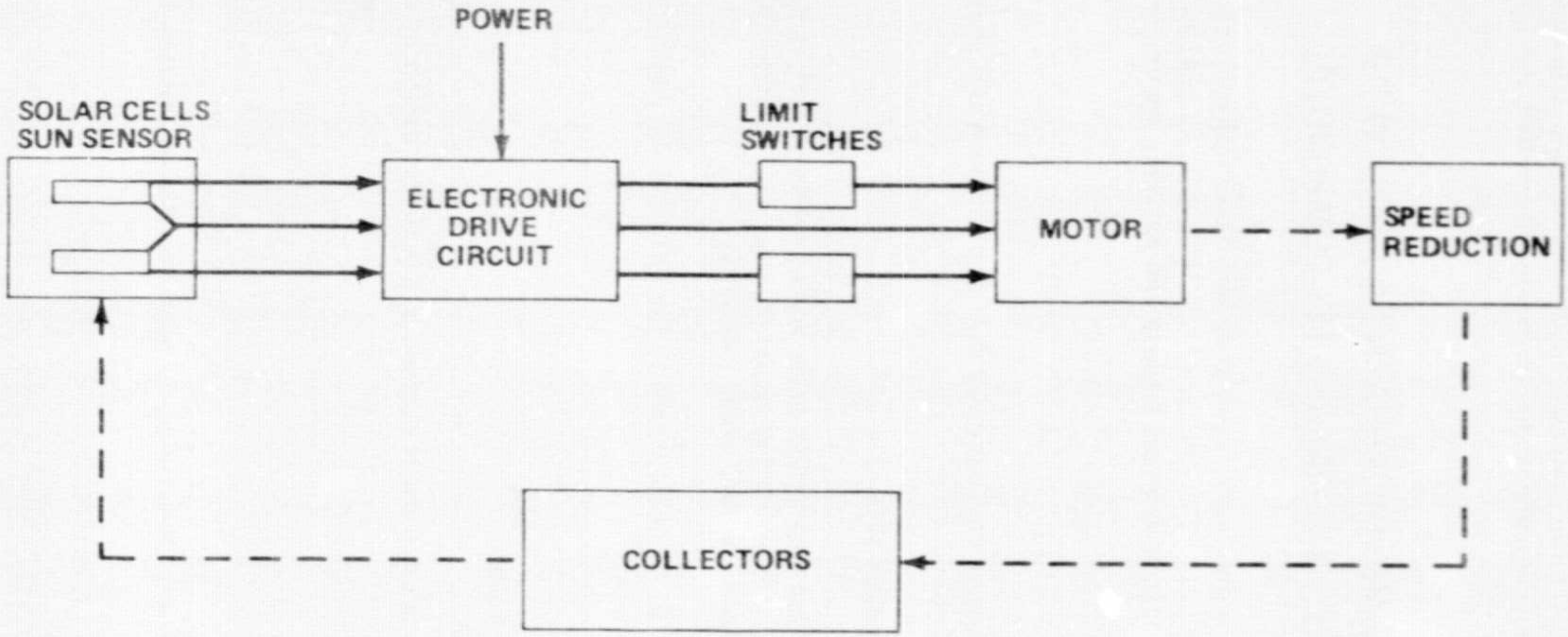

Figure 2. Block diagram schematic of the controller system.

the motor. The motor drives the collector about its gimbaled axis through a speed reduction of 448 000:1 to reduce the error signal and turn the motor drive off.

ANALYSIS AND OBSERVATIONS MADE ON THE CONTROLLER SYSTEM AND ITS COMPONENTS

The following are some tests, analyses, and observations made on the controller and its components. The purpose here is to give an engineering review and analysis, not exhaustive test results and extreme accuracy of measurements.

Sun Sensor

— Produces maximum current of 50 mA at solar noon and approximately 34 mA at 7 a.m. and 5 p.m.

— Approximately 180° FOV

— The current generated by the solar cells is determined by geometry of the solar cells (sizes), transparency of cover, maximum short-circuit current, Sun angle to the sensor, and solar intensity.

— The difference in current, which is the error to the controller, is given by the following equation:[1]

$$i_2 - i_1 = 3.5\, I_{SCM} \sin \phi \quad ,$$

where I_{SCM} is maximum short-circuit current and ϕ is the angle of Sun rays to the solar cell.

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1. Northrup Quarterly Report No. 10046-4, page 39. Dated January 20, 1977.

Electronics

— A difference voltage generated from the solar cell output current across a 10 Ω resistor feeds an op-amp with a gain of 300. When this output reaches 0.55 V, transistor Q1 or Q3 breaks down depending on the sign and latches on with positive feedback to direct 12 V through a relay coil (Figure 3).

— From the above one can determine the error angle of the Sun's rays on the sensor that cause the circuit to energize the relays (collector drive on) and when the relays will de-energize (collector drive off).

$$e_2 - e_1 = 3.5\, I_{SCM}\, R \sin\phi\,, \quad \text{where} \quad R = 10\,\Omega\,.$$

The output of the op-amp:

$$e_o = 10\,500\, I_{SCM} \sin\phi$$

$$0.55 = 10\,500\, I_{SCM} \sin\phi$$

$$\phi = \sin^{-1} \frac{0.55}{10\,500\, I_{SCM}}$$

At noon $I_{SCM} = 0.05$ A

At 5:00 p.m. $I_{SCM} = 0.0347$ A .

The system will turn on or start to drive at

$$\text{Noon } \phi = \sin^{-1} \frac{0.55}{10\,500\,(0.05)} = 0.06°$$

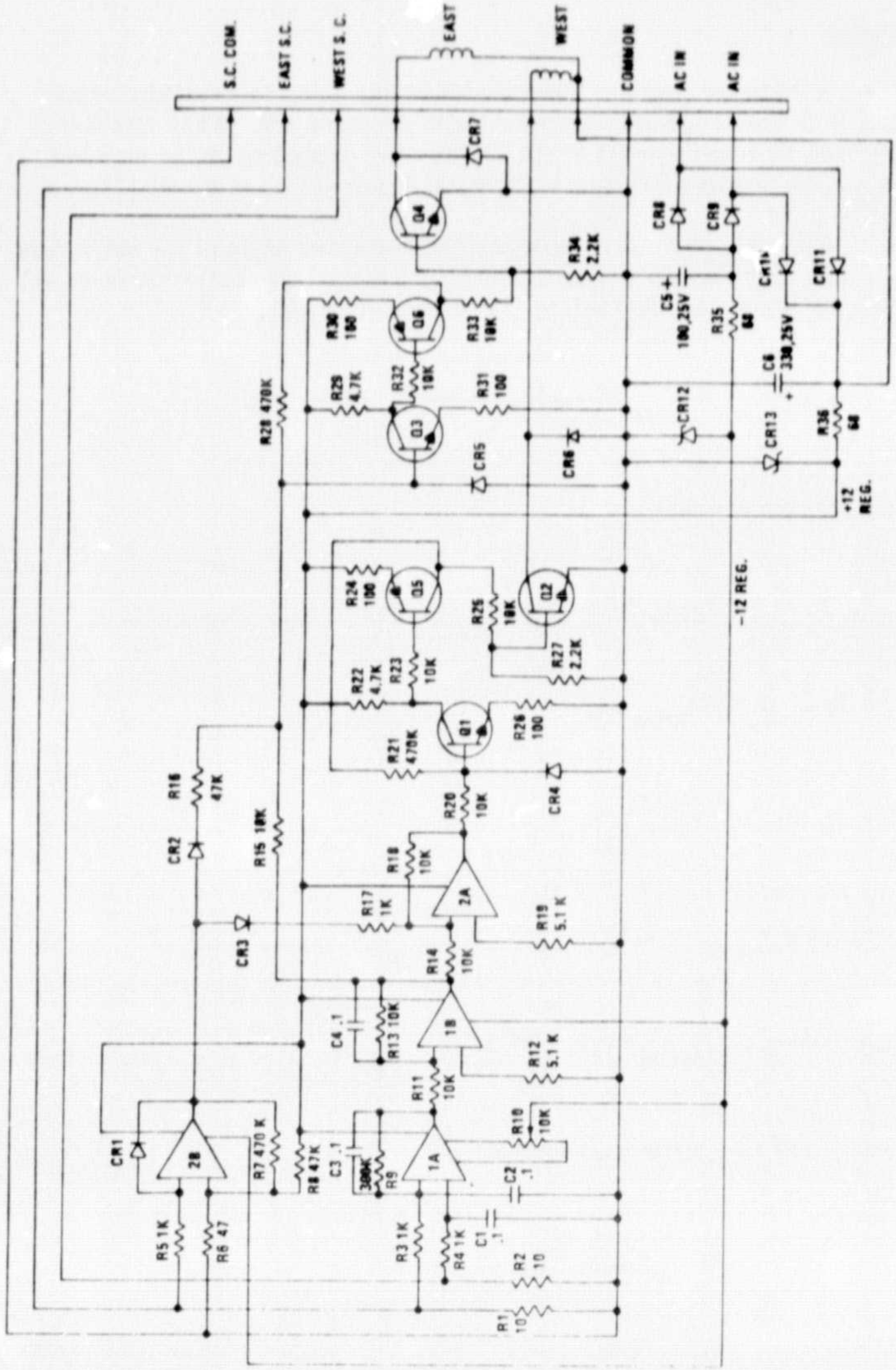

Figure 3. Northrup controller circuit.

$$5{:}00\ \text{p.m.}\quad \phi = \sin^{-1} \frac{0.55}{10\,500\,(0.0347)} = 0.086° .$$

Hysteresis

— There is a 0.25 V positive feedback loop to provide hysteresis. When the system drives the Sun sensor to reduce the error signal by this amount (0.25 V), the motor drive will stop. The system turns off according to the following:

$$\text{Noon}\ \phi = \sin^{-1} \frac{0.55 - 0.25}{10\,500\,(0.05)} = 0.033°$$

Amount driven 0.06 - 0.033 = 0.027°

$$5{:}00\ \text{p.m.} = \sin^{-1} \frac{0.55 - 0.25}{10\,500\,(0.0347)} = 0.047°$$

Amount driven 0.086 - 0.047 = 0.039° .

When comparing the amount driven with the original error signal, it is obvious the system never drives to zero. Also the amount driven is extremely small.

Drive Rate

— The rate of drive for the collector can be determined by knowing the motor speed and the reduction:

Motor Speed 3200 rpm

Speed reduction 448 000:1

$$\frac{3200\ \text{rpm}}{448\,000} \times 360°/\text{R} = 2.57°/\text{min} .$$

Duration

Nominal on-time is:

$$\frac{0.027°}{2.57°/\text{min} - 0.25°/\text{min}} = 0.7 \text{ sec at noon}$$

$$\frac{0.039°}{2.57°/\text{min} - 0.25°/\text{min}} = 1.0 \text{ sec at 5 p.m.}$$

where 0.25°/min is Earth's rate.

Traverse Distance

The linear distance the cable drive travels

$$\text{Noon } \frac{3200}{448\,000} \text{ rpm} \times 35 \frac{\text{in.}}{\text{rev}} \times 0.7 \text{ sec} = 0.0029 \text{ in.}$$

$$\text{5 p.m. } \frac{3200}{448\,000} \text{ rpm} \times 35 \frac{\text{in.}}{\text{rev}} \times 1.0 \text{ sec} = 0.004 \text{ in.}$$

Motor

— Two Pole/3200 rpm

— Requires 0.32 A at 120 V without collector load. Motor plus electronics draws about 0.40 A at 120 V

— Start current 50 percent higher and goes to normal in 0.1 sec

— Power factor 70 percent

— Temperature rise from ambient of 70° to 120°F in about 10 min of continuous run

— Measured motor torque approximately 0.2965 in.-lb

— Measured torque through 800:1 gear reduction 105 in./lb

— Torque gain through 800:1 gear reduction 354 or 0.44 efficiency

— Temperature after 45 min of continuous run in 44°C ambient 80°C (Fig. 4)

— Torque speed curve (Fig. 5)

— Motor stall temperature rise over 15 min (Fig. 4).

Gears

— 800:1 gear reduction in the control box to output shaft is an integral part of the motor

— 448 000:1 total reduction from the motor shaft to the collector shaft

— 16 threads/in. or 16 rev/in. rotation to linear motion

— 35 in./rev linear to rotational motion.

BREADBOARD ELECTRONIC CIRCUIT

The new electronic circuit for the controller was breadboarded with like or equivalent components. Some changes that should be noted are as follows:

a. Relays used on the breadboard circuit were 2 A with a coil resistance of 120 Ω. The relay specified was a 10 A with 100 Ω coil resistance.

b. The filtering capacitors used for the 12 Vdc supply were 220 μf, 50 V instead of 100 μf, 25 V across the -12 V and ground. Across the 12 V and ground, a 470 μf, 25 V capacitor was used instead of a 330 μf, 25 V.

c. Two 741 op-amps were used to replace the 747 dual op-amp specified.

d. The power supply input voltage to the circuit measured about 15 Vac instead of 12 Vac as related on the schematic.

All other components were the same or equal to those on the parts list, dated July 29, 1977, from Reich Associates, Inc.

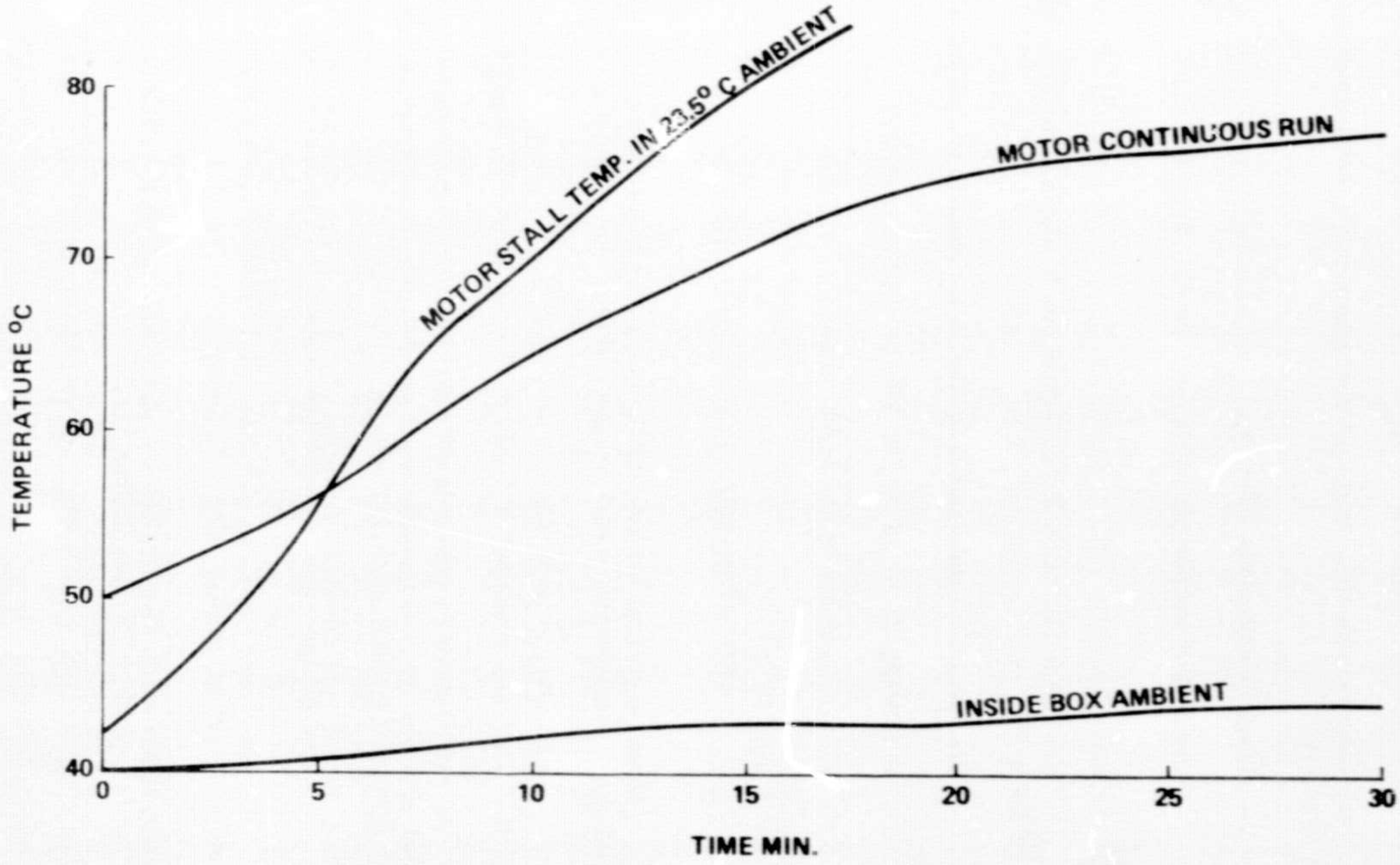

Figure 4. Motor temperature versus run time.

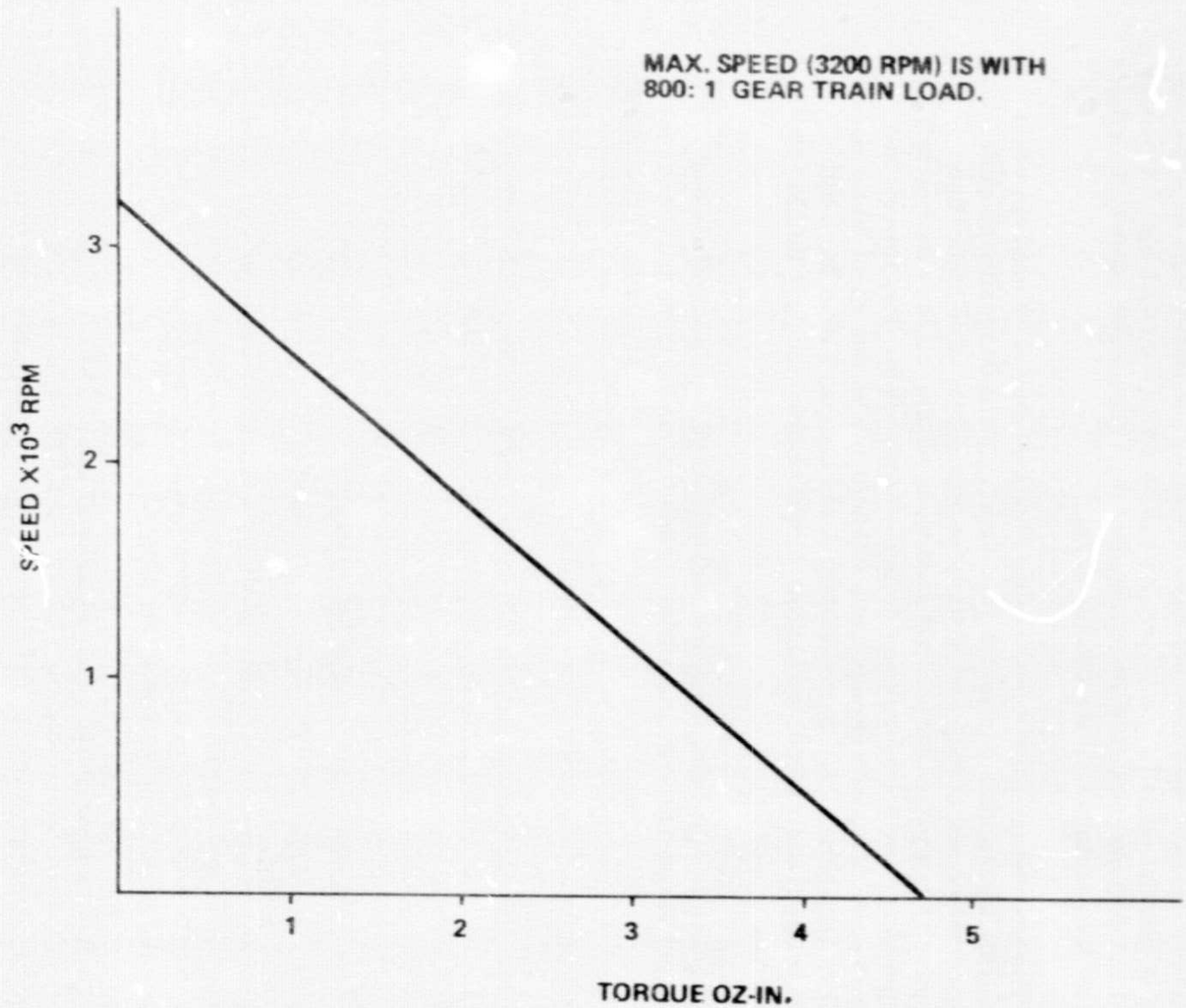

Figure 5. Motor speed/torque curve.

CIRCUIT ANALYSIS

The circuit analysis program used to do the nominal and worst case analyses is called CIRC-DC. It was developed by Xerox Data Systems and does a complete dc analysis with variable input capability for such things as hysteresis or other sequential circuit operations. Its semiconductor models use data easily obtained and well understood by circuit engineers. The models include the effects of junction temperature as a standard feature.

The nominal analysis is made using blueprint circuit values. In worst case analysis a particular parameter (one or many) can be monitored while trying each component at each end of its tolerance range. The highest and lowest value of that parameter are retained together with all the other circuit values and conditions that contributed to those worst cases. For this circuit there were some 300 pages of output in a full analysis versus about 30 for one or two nodes. It requires only approximately 6 min computer time for a full analysis (with no convergence problems) versus approximately 1 min for one or two nodes.

The hysteresis runs, using nominal circuit values, sometimes had trouble when the circuit was supposed to switch. Jumping these particular spots, once they were determined by trial and error, solved the problem. These switch points in the normal operating region were on at 0.62 V and off at 0.35 V calculated at the output of the first op-amp.

After the circuit was modified to include all the recommendations, another hysteresis run was made. The switch points then were on at 0.62 V and off at -0.10 V.

POWER SUPPLY

The worst case circuit analysis shows a maximum current of 181 mA drain from the power supply with 17 mA maximum from the regulated 12 V. The minimum current drawn from the power supply is approximately 4 mA each from the regulated plus and minus supply.

This gives a maximum power of 363 mW for R36 which is a 500 mW resistor, and a maximum power of 829 mW for CR13 which is a 1 W zener. The 1N4004 rectifiers are 1 A, 400 V devices with a maximum average

current of only 60.5 mA. Capacitors C5 and C6 are rated at 25 V and experience a maximum voltage of 16.97. Therefore, the power supply design appears adequate, with some margin on each component.

RESULTS OF THE HARDWARE TESTS

The breadboard circuit was interfaced with the Sun sensor, motor and drive train, and tests were conducted to determine the adequacy of the new circuit. There was no collector load on the motor output.

On a hazy day with no clouds near the Sun, the control system cycled the system on and off as predicted in the previous calculations (Fig. 6).

On a day when there were cumulus clouds near or covering the Sun, part of the time the controller would drive either east or west, depending on the cloud position relative to the Sun (Fig. 7).

In the test performed during cloud cover, the solar cell was always unbalanced enough to produce a differertial voltage that would drive the system either east or west. In this case a 50 percent or greater cloud cover would totally defocus the collector. Anything less than 50 percent would reduce the efficiency of the collector proportional to the amount of cloud cover.

Tests were performed with line voltages of 100 and 135 Vac which did not appear to affect the proper functioning of the controller. However, an occasional cloud covering the Sun prevented a long duration test.

A large voltage spike (75 V) was noted on the output transistor collector driving the relay coil when the transistor turned off. A diode across the transistor collector and emitter was removed and installed across the relay coil. This made the circuit work much better with no voltage spike or relay chatter when the transistor turned off.

Based on the test results, the expected accuracy is as follows:

Bright Sun — 0.06° at noon, 0.086° at 7 a.m. and 5 p.m.

Hazy Sun — Slightly less than a bright Sun depending on the intensity of the haziness.

Partly cloudy — Total defocus when 50 percent or more cloudy. Accuracy with less than 50 percent cloud proportional to the percent cloud cover.

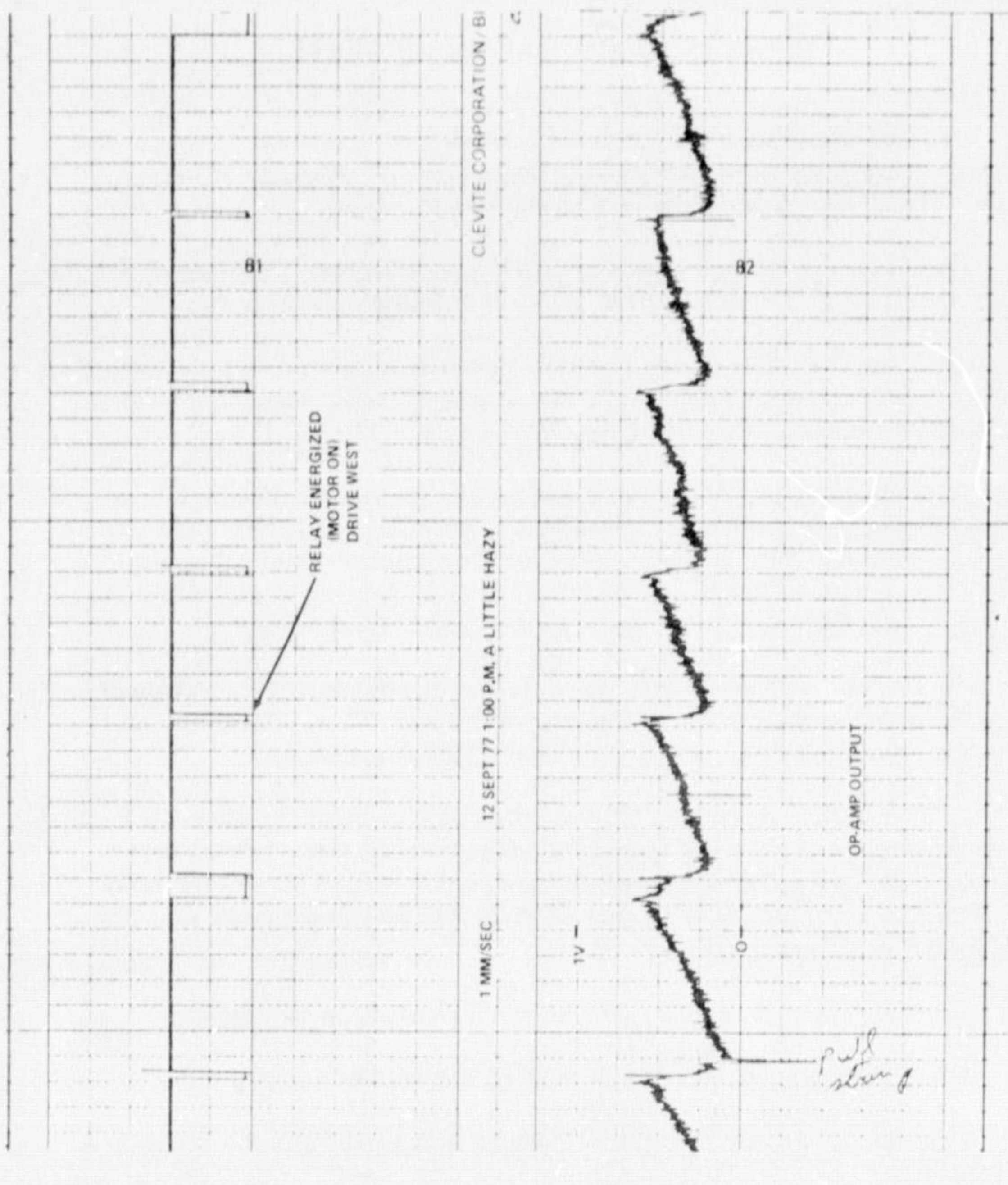

Figure 6. Controller tracking Sun without clouds.

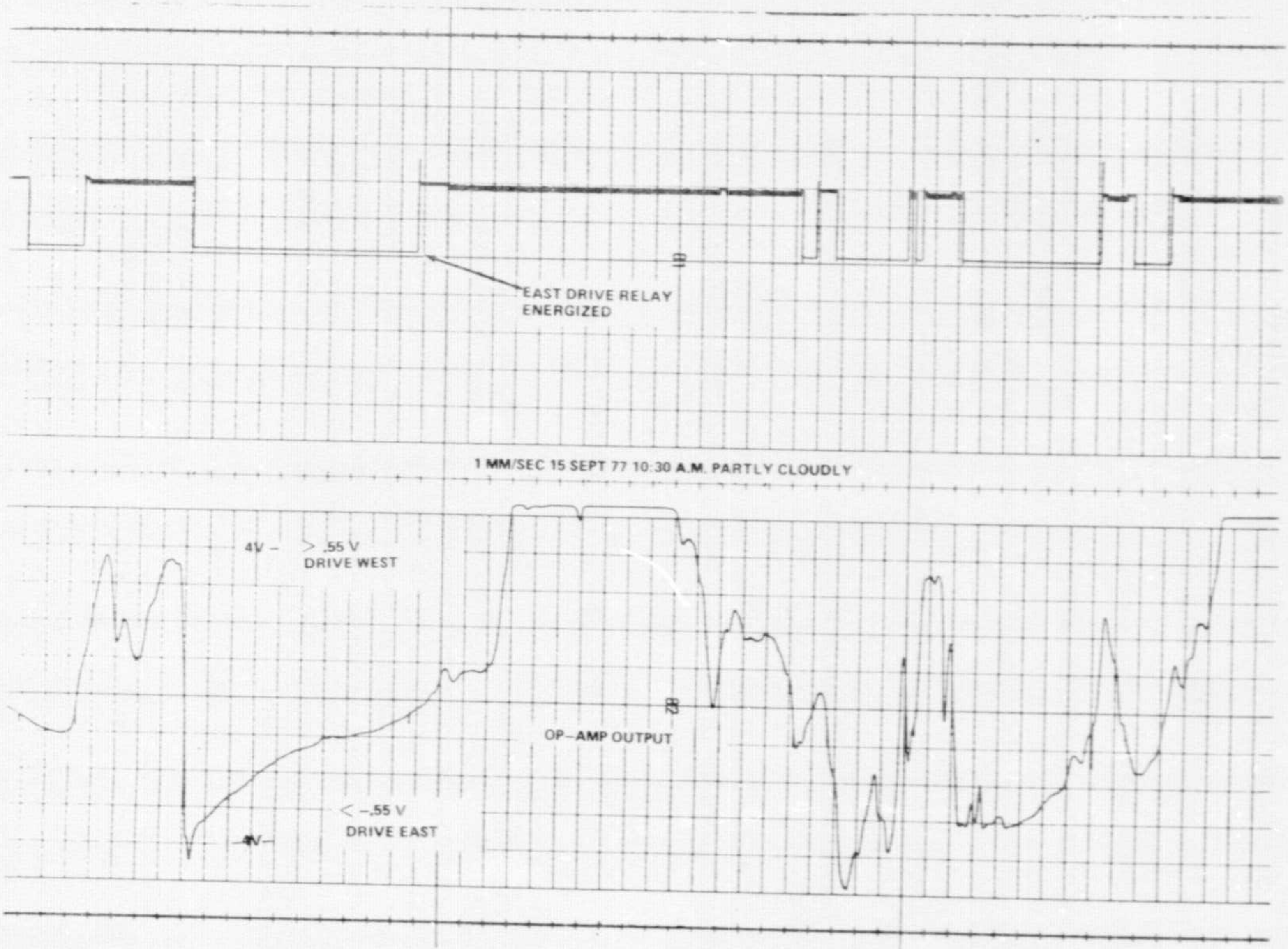

Figure 7. Controller tracking Sun partly cloudy.

RECOMMENDATIONS BASED ON HARDWARE TESTS

The sensitivity is reduced by halving the input op-amp gain from 300 to 150. This change would double the error signal of Sun rays incident on the collector from 0.06° to 0.12° at noon without degrading the efficiency.

The hysteresis should be increased by a factor of 3 by increasing the positive feedback voltage in the transistor circuit from 0.25 to 0.75 V. This could be accomplished by reducing the feedback resistance by 1/3. The increased deadband will reduce on/off cycling and will not degrade the efficiency of the collector. With the increase in hysteresis, the error angle of the Sun rays striking the fresnel lens will cycle through zero error rather than off to one side of zero error.

The Sun sensor should be modified to prevent random driving during cloud cover.

The diodes across the collector and emitter of the output transistors should be removed and placed across the relay coils to prevent high voltage at cutoff.

RESULTS OF CIRCUIT ANALYSIS

Two basic problems were revealed by circuit analysis: the diodes on the output stages should be around the relay coils rather than the output transistors, and the output stages have insufficient drive to remain in saturation under minimum gain conditions specified for the transistors. This drive deficiency is severe enough to cause the relay current to drop to approximately 30 mA under worst case conditions and the power in Q2 and Q4 to exceed 1/2 W under other worst case conditions, although not simultaneously. Since the 2N2222 is rated at 500 mW at 25°C and derated 3.3 mW/°C, this condition could become catastrophic.

A less important deficiency in the circuit design is the fact that R22 and R29 are tied from the collectors of Q1 and Q3, respectively, instead of from the bases of Q5 and Q6 as they should have been (Fig. 3). This change assures cleaner switching with more predictable hysteresis voltage points.

These problems and deficiencies were verified by computer analysis. Two nominal computer runs were made on this circuit: one at normal operating light levels, showing the hysteresis in the output stage, and one at low light levels showing the operation of the east drive circuit. With the exception of the output diodes, these runs showed satisfactory operation of the circuit. Two worst case computer runs were made, one with the input varying and one with a fixed input, to best show the different aspects of the circuit.

After the analysis of the original circuit was completed, the modified circuit was analyzed. Two nominal computer runs and a worst case analysis were made. The problems observed in the original circuit are no longer present, and no new problems appeared.

RECOMMENDATIONS BASED ON CIRCUIT ANALYSIS

It should be noted that two of the changes recommended in the circuit are the result of field testing and are not due to circuit deficiencies, as such. These recommendations are a reduction in the gain of the first amplifier and an increase in the hysteresis in the output stages.

A schematic showing the recommended circuit modification is included in this report (Fig. 8). The recommended modifications are as follows:

1. Change R9 from 300 to 150K.

2. Change R21 and R28 from 470 to 150K.

3. Move one end of R22 (4.7K) from the collector of Q1 to the base of Q5.

4. Move one end of R29 (4.6K) from the collector of Q3 to the base of Q6.

5. Change R25 and R33 from 10 to 2.4K.

6. Move CR6 and CR7 from across Q2 and Q4 to their respective relay coils.

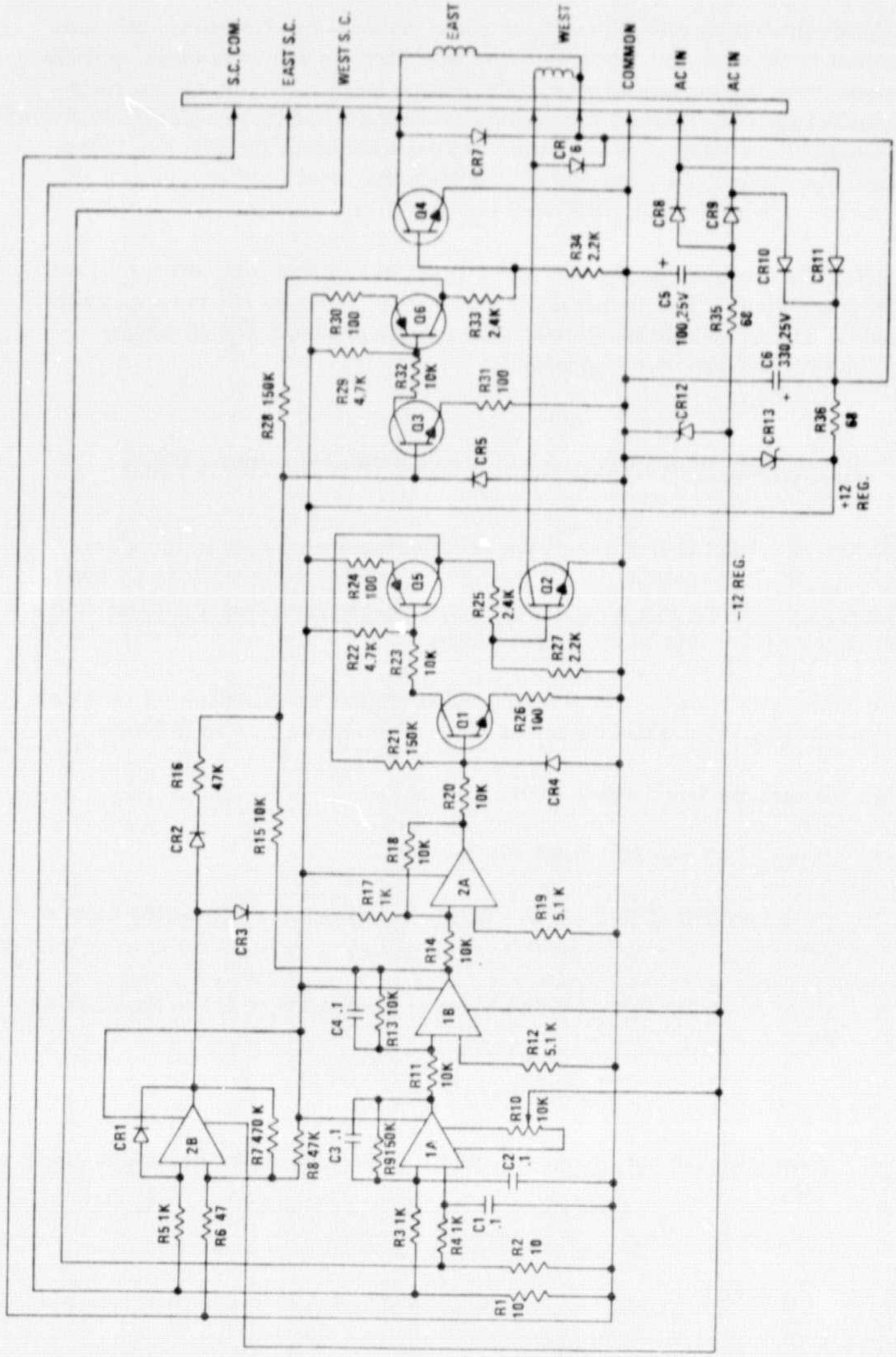

Figure 8. Recommended controller circuit.

CONCLUSIONS

A circuit analysis was performed with worst case maximum and minimum as well as nominal parameter conditions. The data indicate that the circuit will function properly under normal conditions but will not function properly under certain worst case conditions. The analysis shows that the circuit will function properly under all conditions with the recommended changes. Further, system tests were performed with the controller system utilizing a breadboarded circuit. These tests indicate improvements can be attained by reducing the sensitivity of the circuit, thereby reducing on/off cycling. In addition to the circuit modification, the Sun sensor should be modified to better track the Sun under cloudy conditions.

APPROVAL

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The information in this report has been reviewed for security classification. The report, in its entirety, has been determined to be unclassified and contains no information concerning Department of Defense or Atomic Energy Commission programs.

This document has also been reviewed and approved for technical accuracy.

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